Ocean Battlespace Sensing (OBS) S&T Department Annual Report
High resolution upper ocean microstructure measurements in the Bay of Bengal

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LONG-TERM GOALS

To understand turbulent mixing in the ocean and develop physically based parameterizations for use in regional and global numerical models.

OBJECTIVES

Our work for the ASIRI project is designed to

1. Understand the processes controlling freshwater distribution in the Bay of Bengal
2. Explore the physics behind upper ocean mixing in this region to better constrain the heat available to fuel atmospheric phenomena
3. Develop better parameterizations of upper ocean mixing processes suitable for regional models, in particular monsoon prediction models
4. Foster scientific exchange and collaboration with Indian and Sri Lankan colleagues

APPROACH

A series of ship-based process experiments is being carried out. The tools we are contributing to the overall experiment include

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- **χ-pods**: A new generation of miniaturized χ-pods were developed at Oregon State University and integrated into the drifting profiling Wire-walker instruments deployed by Lucas and Pinkel. A total of six mini-χ-pods have been fabricated and have been used for multiple profiling deployments. Some results are presented here and also in Lucas/Pinkel's annual report.
- **Bow Chain**: To measure undisturbed near-surface density and turbulence and to capture finescale horizontal gradients of near surface features, we deployed a 10-m long, 20 element chain of T, CT and χ-pod sensors from the foremost opening on the Revelle's foredeck. Sensors were sampled quickly (ranging from 2 Hz to 100 Hz), and their motion determined using a series of fast-sampled accelerometers. Combined with 6 Hz pressure records, this system allows us to remove wave contamination from the CTD records, which is effectively at 50 cm in the vertical and 1 m in the horizontal.

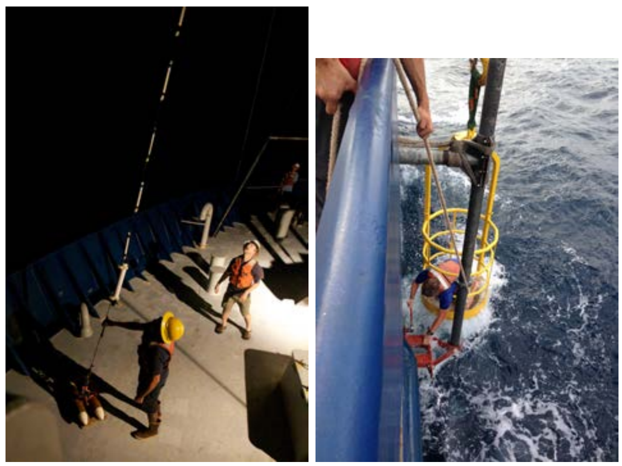

Figure 1: Left: Nighttime deployment of the bow chain. Right: adjustment at sea of the side-pole-mounted 5-beam ADCP.

- **Near-surface ADCP**. To supplement sonars permanently installed in the ship hull, two additional ADCPs were utilized during this experiment. A 300-kHz RDI ADCP was installed in an open well in the staging bay. This instrument was set to sample in 4-meter vertical bins with 1-second sampling. To acquire data even closer to the surface and additional 500 kHzADCP was installed at the end of a pole mounted to the side of the ship (Fig. 1, right). The instrument is a 'Sentinel V', a newly available instrument from RDI Teledyne (http://www.rdinstruments.com/followV.aspx). In addition to a standard 4-beam Janus configuration it has a fifth vertically oriented beam. The addition of the fifth beam allows more accurate estimate of two-variable correlations such as Reynolds stresses. In order to avoid one of the beams hitting the ship hull, the instrument was mounted at a 15 degree angle to the vertical, pointing away from the ship.

WORK COMPLETED

Our efforts have been part of three process cruises undertaken in the past year:

Early November 2013

Leg-1 of the ASIRI Pilot cruise was primarily a small-scale (submesoscale) process study. The general sampling strategy was to utilize the Revelle's extended shipboard sampling capabilities to sample small

lateral scale features in the context of drifting profiling assets. This approach allowed for repeated horizontal surveys of evolving submesoscale features gathered concurrently with high resolution time series observations from the drifting instruments. These complementary approaches provide the detailed horizontal, vertical, and temporal resolution necessary to examine submesoscale dynamical variability *in situ*.

We utilized remote sensing products and real-time shipboard data, particularly from the flow-through system and the underway CTD (UCTD), to target general areas and then hone in on small-scale dynamics of interest. Based on the remote sensing information shared by our Indian colleagues, we conducted sampling activities centered around 2 locations: 15°N 86°E (14-16 November, 2013) and 16°N 87°E (17-23 November, 2013). Upon arrival at both locations, we conducted a preliminary survey utilizing the shipboard sampling and UCTD. We subsequently deployed 3 χ-pod-equipped Wirewalker (WW) wave-powered profilers (see below) and a densely instrumented spar buoy. Once the drifting assets were deployed, we typically lowered our over-the-side 500 kHz ADCP and instrumented bow-chain, and resumed horizontal survey activities, utilizing the drifting array as an anchor for our drifting surveys. During deployments of the over-the-side pole and bow chain, our forward speed was limited to $\sim$3 knots, leading to very fine spacing of UCTD casts during slow speed survey mode. We augmented these surveys with a series of sections and casts of a microstructure profiler (Rockland Scientific VMP-250) brought aboard and managed by Sri Lankan collaborators and Iossif Lozovatsky.

Late November / Early December 2013

A second process cruise was led by Shroyer and Mahadevan. This leg covered a much larger area of the Bay. However, they did spend some time doing small-scale surveys as well, using some of the tools we suppled (e.g. side-pole-mounted ADCP).

June 2014

A successful cruise took place from 17-28 June onboard R/V Revelle in the western Bay of Bengal. A variety of observational platforms were used to 1) map the large-scale ($>$ 100 km) physical context and 2) record the evolution of the upwind and downwind edges of a salty filament. The cruise consisted of two major components: 1) a large-scale rapid survey and 2) two smaller scale high-resolution surveys. During the later component, our bow-chain and high-resolution ADCP were deployed, yielding further insights into upper ocean dynamics.

RESULTS

Analysis is ongoing. Here we highlight three of the more exciting results to date.

Nonlinear, dissipative near-surface bore

We had several opportunities to observe strongly nonlinear bores. Figure 2 shows temperature from the ship through flow system during multiple bore crossings. There is a strong temperature jump visible in each of 8 crossings. During the several hours of this survey the front moved northward at a slowing rate. The temperature on the warm side of the front steadily decreased, which we interpret as a cold, freshwater layer propagating over a warmer, saltier water with an underlying N-S gradient. The front is starkly visible in the bow chain data, with a front of mere meters in width! (Fig 2). Velocity from the side pole mounted ADCP shows a strong convergence in surface velocity. We hypothesize that the bore was created after along-front wind stress led to differential Ekman transport in the cross-front direction that steepened the salinity gradients the point of nonlinear bore propagation. Preliminary analysis

indicates the bore propagation speed is consistent with $c_{bore} \sim \sqrt{g'h}$. The bore was highly turbulent, as can be seen in the interleaving temperature from the bow chain data (Fig. 2, left), suggesting that such features may be an important and previously under-appreciated mechanism for mixing the upper ocean. These results are being written up for submission in Fall 2014.

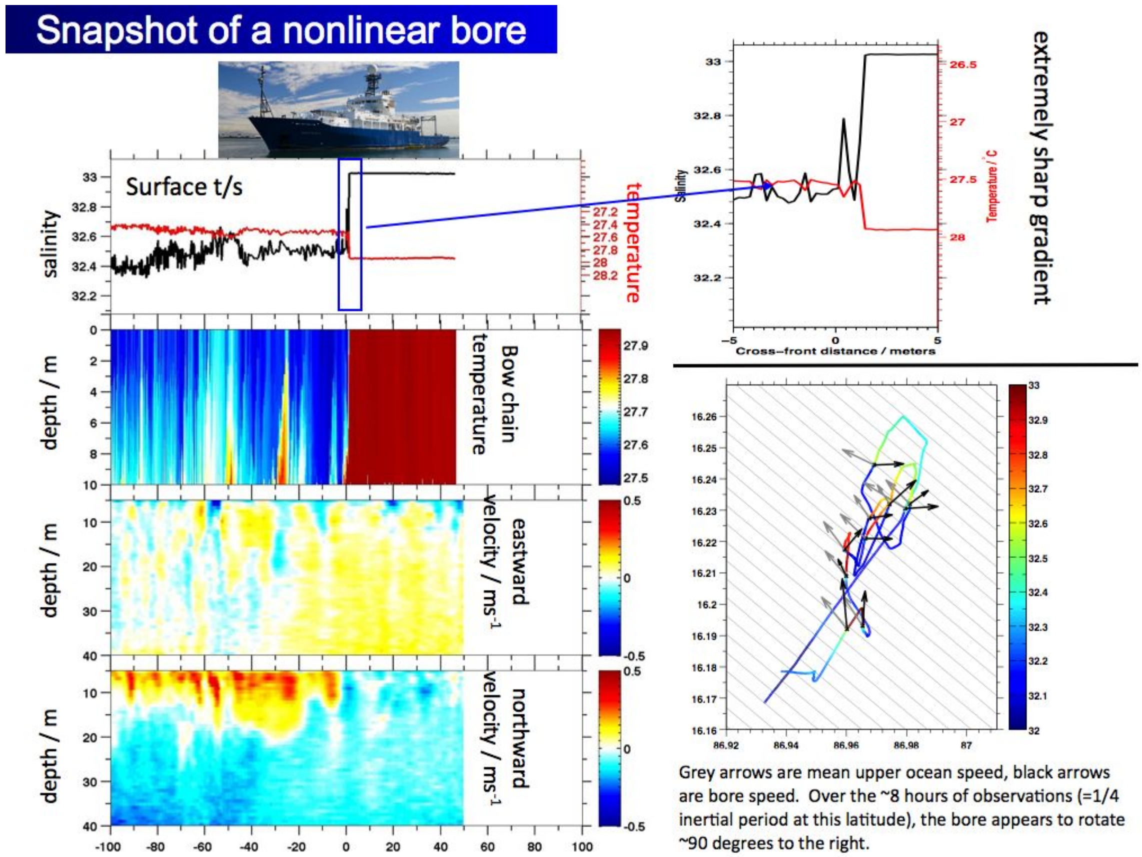

***Figure 2:** A snapshot of an extremely nonlinear surface bore observed during the first process cruise. Left panels show one pass through the bore as evidenced in bow-chain measurements of salinity and temperature, and currents from the side-pole mounted ADCP. The Revelle is shown for scale, so one can appreciate the extremely sharp nature of the front (much smaller than the ship itself). Upper right shows a zoom in on the front, over which salinity jumps by about 0.5 psu over 1 meter horizontally. Lower right shows surface salinity for all of our passes over this bore.*

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Lateral upper ocean variability

High resolution upper ocean measurements taken with both ADCPs and the bow-chain while underway allow novel and unprecedented look at horizontal variability in the upper ocean. Careful analysis of statistics of both velocity and salinity can provide strong clues as to underlying dynamics, and in particular facets of those dynamics that are unique to the Bay of Bengal and instrumental in setting upper ocean fluxes and air-sea exchange rates. Figure 4 shows an example of lateral spectra of near-surface temperature (red; essentially a passive tracer in this salinity-dominated environment) and velocity(black). Large-scale quasi-geostrophic theory, as well as previous observations, predict steep spectra, with slopes of -5/3 to -2, that represent the effect of stirring by large-scale eddies. Our observations to replicate such statistics at large scales (>10 km). However, our novel instrumentation

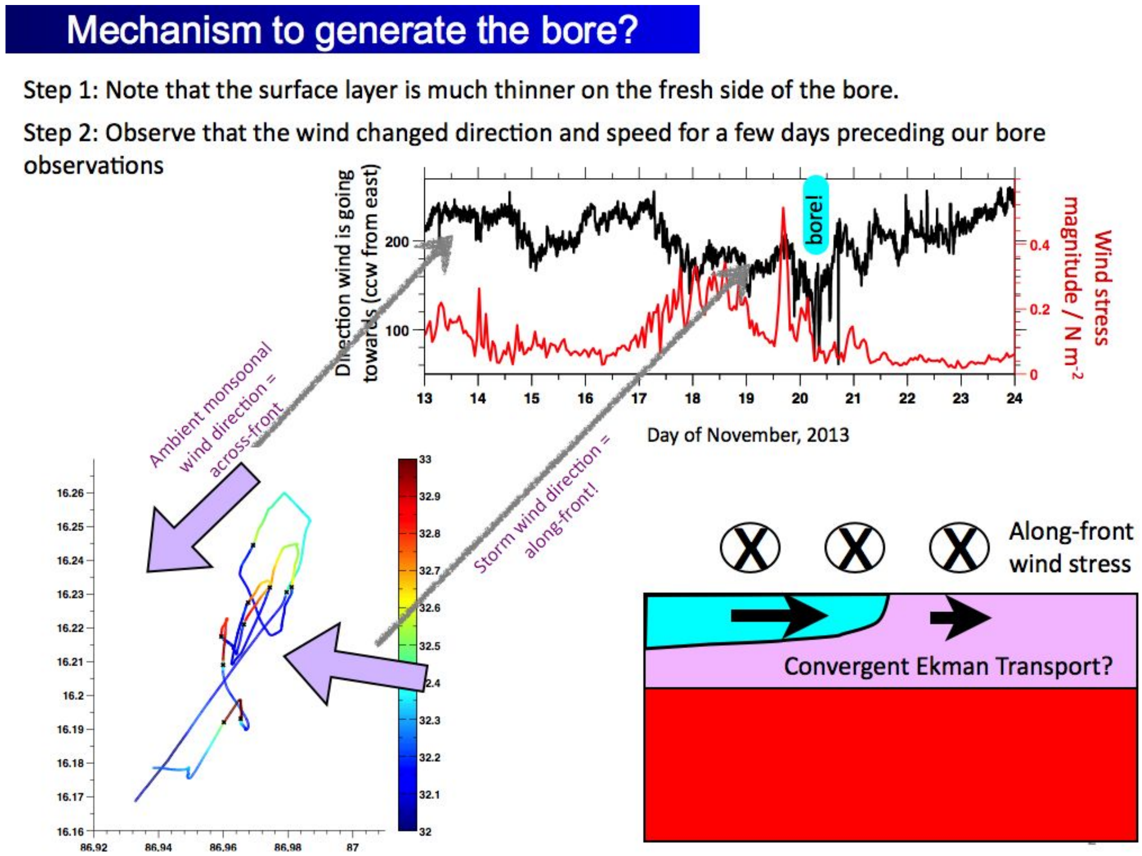

Figure 3: ***Preliminary analysis of mechanisms that may have generated this bore. The bore is propagating on large-scale salinity gradient. Preceding our bore observations, ambient winds were in the across-front direction. Right before we observed the bore, a passing storm produced winds in the along-front direction, which would lead to Ekman transport in the cross-front direction. The fresh side of the front had a much shallowed surface mixed layer, suggesting that for the same wind strength Ekman currents would be much faster, as momentum is distributed over a smaller vertical range. This could lead the fresh later to a cross-front convergent velocity (as directly observed in Figure 2) and a sharpening of the front. As winds relaxed, this front would be 'released' to propagate as a nonlinear bore.***

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also allows us to look at variability on much smaller scales, from kilometers down to meters. Here we find a rich range of surprising results. Specifically, at about 1 km wavelength (10^{-3} cpm wavenumber), there is a surprising peak in kinetic energy (velocity variance). Almost exactly at this point the temperature spectrum changes to a much shallower slope. We identify this as strong evidence for an energetic sub-mesoscale; 1 km is probably not coincidentally the Rossby wavelength appropriate for the observed surface layer depth and stratification, it is the expected wavelength of the fastest growing mode for a "mixed-layer instability" (essentially baroclinic instability localized to the surface layer). We interpret the change in slope of the temperature spectrum as evidence that tracers on these scales (1 km and smaller) are stirred by sub-mesoscale dynamics rather than large-scale eddies, as is typically the case. These are tentative conclusions so far, but we are excited to continue in this vein of analysis, and are hopeful such work will lead to fundamentally new insights into the nature of upper ocean stirring and mixing in the Bay of Bengal.

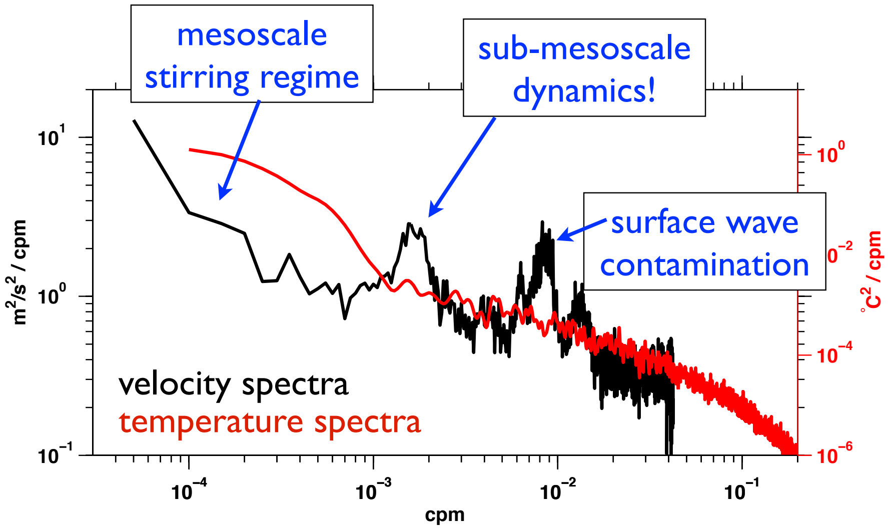

Figure 4: ***Example horizontal spectra of near-surface velocity (back, left y-axis), and temperature (red, right y-axis). Velocity data from 8 meters depth, from the ADCP placed in the pipe string, temperature data from the bow-chain, in the upper 10 meters of ocean.***

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Intrusion-induced intense mixing events

Filaments and finescale instabilities were observed in detail by both the **spar buoy** and **χ-pod-wirewalkers**. The observed intrusions are strong (they are sufficient to transport mass > 10 km/day), and also provide sufficient shear to generate turbulent instabilities and drive significant vertical heat fluxes, as demonstrated through two, multi-day χ-pod-wirewalker records (Fig. 5). Importantly, the timing and location of highest mixing corresponds with the strongest lateral intrusions.

Initial comparisons between a region of weak large-scale horizontal gradients (Fig. 6, left) and a region dominated by larger scale gradients in an actively straining mesoscale (Fig. 6, right) show marked differences. While at depths below 60 m (lower panels), there is little difference, the upper ocean exhibits marked contrasts in these two scenarios, with respect to both lateral/temporal variability, the role of night-time convection, and the ability to detect the subsurface structure from space.

IMPACT/APPLICATIONS

It is anticipated that the present work will improve our understanding of upper ocean heat transport and related processes in the Bay of Bengal. This, in turn, should improve the fidelity of regional forecast models.

TRANSITIONS

N/A

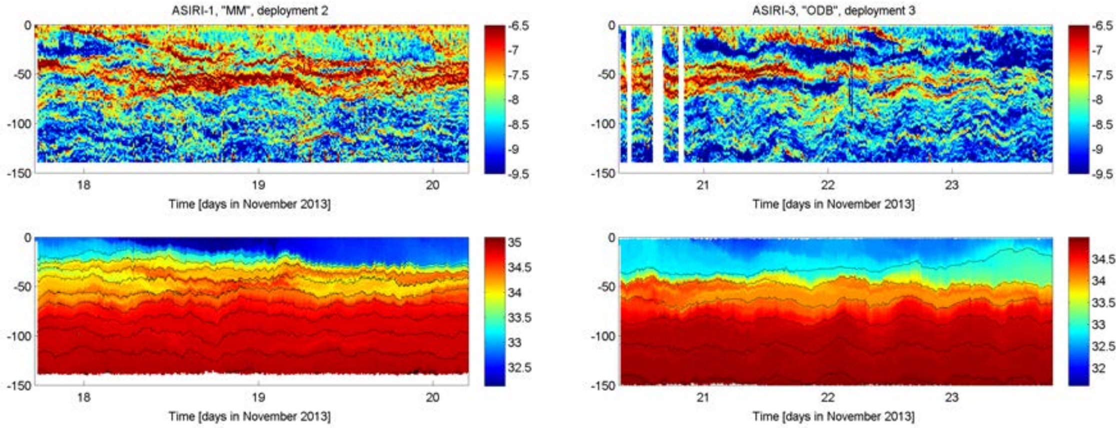

***Figure 5:** Temperature variance dissipation rate (top; K^2/s) and salinity (bottom; PSU) for two deployments of the χ-**pod-wirewalker** (deployed by Lucas et al) where active submesoscale interleaving produced enhanced turbulent dissipation rates within the barrier layer. Also evident in the panels to the left is an active surface boundary layer with several pulses of turbulence that expand downwards.*

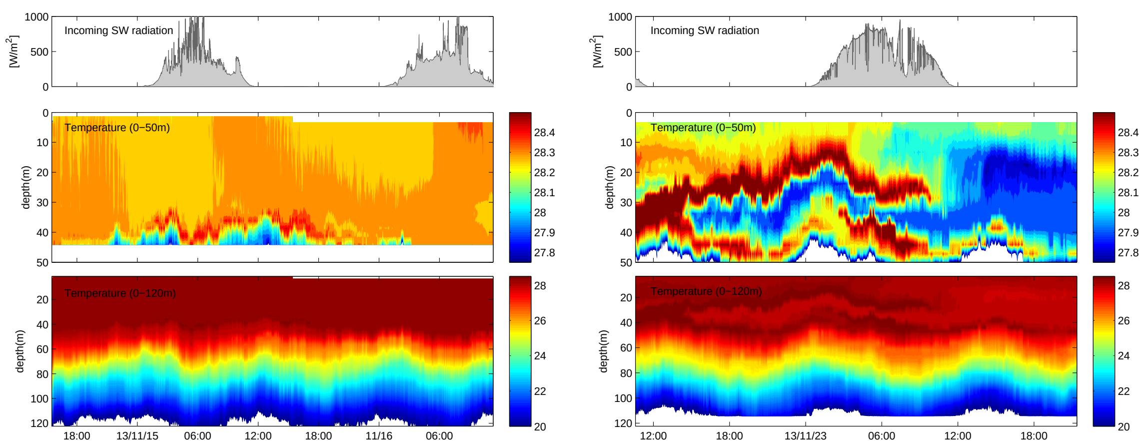

***Figure 6:** Contrasts between a pair of 36-h records of temperature from the* **spar buoy.** *Left panels show the temporal evolution in a location with weak horizontal density gradients, resulting in a deep and homogeneous mixed layer with visible periods of nighttime convection down to 40 m. Right panels show a time series at a location where increased horizontal density gradients give rise to significant lateral intrusions with 0.4 C temperature anomalies. Also evident at both locations is a 20-m amplitude internal tide at depth.*

RELATED PROJECTS

Both PIs are also both participants in an NSF and NOAA-funded Climate Process Team on ocean mixing, tasked with improving representations of turbulent mixing in global and regional scale numerical models. Results obtained by the presently proposed work would be directly transferable to ongoing CPT efforts, in conjunction with national modeling centers. (http://www-pord.ucsd.edu/~jen/cpt/).

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A. Lucas, E. Shroyer, H. Wijesekera, H. Fernando, E. D'Asaro, M. Ravichandran, S. Jinadasa, J. MacKinnon, J. Nash, R. Sharma, et al. Mixing to monsoons: Air-sea interactions in the Bay of Bengal. *Eos, Transactions American Geophysical Union*, 95(30):269–270, 2014.

PUBLICATIONS

Lucas et al. (2014)

HONORS/AWARDS/PRIZES

MacKinnon was honored to received the Fofonoff early career award for 2014 from the American Meteorological society.